High energy cosmic ray particles and the most powerful new type discharges in thunderstorm atmosphere.

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Abstract

The runaway breakdown – extensive atmospheric shower discharge (RB - EAS) excited in thunderstorm atmosphere by high energy cosmic ray particles ($\varepsilon_p > 10^{17} - 10^{19}$ eV) generate very powerful radio pulse. The RB - EAS theory is compared with observations of radio pulses. An agreement between the theory and experiment is established. The existence of nowaday satellite and ground based systems which obtain regularly a large amount of observational radio data could allow to use them in combination with other methods for effective study of high energy cosmic ray particles

1   Introduction

Le Vine (1980) and Willet (1989) studying radio emission from thunderstorms have noted a distinct class of powerful radio pulses. The intensive investigations of this phenomena were performed during recent years. For the measurements the satellite FORTE and specially constructed systems as LASA, EDOT and others were used [Smith et al., (1999),(2002); Thomas et al (2001); Light and Jacobson (2002); Jacobson (2003)]. These studies allowed to establish that the radio pulses having enormous power $100 - 300$ GW are emitted in the wide frequency range by the intracloud discharges in the upper troposphere. The pulses are short time ($\leq 10\mu s$) and have a definite bipolar form. That is why they were called narrow bipolar pulses (NBP). The observations show that these strong radio pulses are accompanied by very weak optic emission only. A detailed analysis of the whole complex of observational data allowed Jacobson (2003) to state that NBP is a new type of thunderstorm discharge quite different from usual lightning. He speculated that it could have relevance to runaway breakdown effect.

Runaway breakdown (RB) is a new physical concept of an avalanche type increase of a number of relativistic and thermal electrons in air proposed by Gurevich, Milikh and Roussel-Dupre (1992). The avalanche can grow in electric field $E \geq E_c$ which is almost an order of magnitude less than the threshold of conventional breakdown. The electrons

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with high energies $\varepsilon \geq (0.1 - 1)$MeV can become runaway and are accelerated under the action of electric field $E > E_c$. Directly this process – acceleration and collisions with air molecules lead to the avalanche type growth of the number of runaway and thermal electrons (Gurevich and Zybin 2001).

Runaway breakdown in air (RB) is stimulated by the presence of a high energy cosmic ray secondaries. Extensive atmospheric showers (EAS) are accompanied by an effective local growth of the number of cosmic ray secondaries and thus have a strong influence on the RB process (Gurevich et al 1999). The combined action of runaway breakdown and EAS lead to the development of RB - EAS discharge – new type of electric discharge where relativistic electrons play a decisive role. RB-EAS discharge is accompanied by strong exponential growth of the number of energetic and thermal electrons, positrons and gamma quants (Gurevich et al 2004a). It can serve for the generation of a strong bipolar radio pulse (Gurevich et al, 2002).

The goal of the present work is to extend a theory of RB - EAS discharge in air to a very high energy range of cosmic ray particles ($\varepsilon_p \geq 10^{17} - 10^{19}$ eV) and to compare the theory with the results of NBP observations.

2   Narrow bipolar pulses (NBP)

Narrow bipolar pulses are isolated short time discharges generated in thunderclouds. They were discovered and first studied by Le Vine (1980) and Willett et al (1989). During last years very intensive and detailed studies of this special type of atmospheric discharge were performed by Smith et al (1999), Rison et al (1999), Thomas et al (2001), Light and Jacobson (2001), Smith et al (2003), Suszcynsky and Heavner (2003), Jacobson (2003) and others. It was established that NBP are compact and energetic intracloud discharge. They are observed in two forms: negative (NNBP) and positive (PNBP). For negative first electric field peak is negative and vice versa for positive.

Main features
1. NBP are high altitude discharges. Their main location (Smith et al 2003)
z= 15 – 20 km for NNBP (sharp peak near 18 km)
z= 7 – 15 km for PNBP (sharp peak near 13 km)
2. Time characteristics of NBP (Smith et al 1999, 2002)
mean rise time $\sim 1 - 2\mu s$
full width at half maximum $\sim (2 - 5)\mu s$
full rise + fall time $\sim (5 - 10)\mu s$
3. NBP is observed as low frequency 0.2 – 0.5 MHz bipolar ground electromagnetic wave with large amplitude. The NBP effective field amplitude was measured simultaneously at several stations situated at different distances R (Smith et al 2002, 2003). Characteristic wave field is

$$E \sim (10 - 30) \left(\frac{100km}{R} \right) V/m$$

4. Electric current pulse, generating NBP is unipolar and its maximum reaches values

$$J_m \sim (30 - 100)kA$$

5. Dipole electric moment change in the cloud determined by NBP discharge is $M \approx 0.2 - 0.8$ Cu km (Smith et al 1999).

6. From the analysis of observational data it follows that the NBP current initiator moves with very high speed. The speed of initiator is determined as $7.3 \times 10^9 - 3.0 \times 10^{10} cm/s$ (Smith et al 1999) or $\sim 10^{10} cm/s$ (Jacobson 2003).

7. The NBP discharge rates is growing with the thunderstorm convection strength (Suszcynsky and Heavner 2003).

HF radio emission

1. NBP is always accompanied by intensive radio emission in a wide frequency range up to 500 MHz (Smith et al 1999).

2. Detailed study of HF emission in the frequency range (26 – 48) MHz fulfilled at the FORTE satellite allowed to establish the following main features (Jacobson 2003):

a. HF emission connected with NBP is always powerful its integrated ERP ≥ 40 kW It is called by Jacobson strong intracloud (IC) pulse.

b Strong IC pulses are *incoherent* in HF range.

c. Strong IC pulses are accompanied by very low optic emission – at least two orders of magnitude less than in usual flashes.

d. Strong IC pulses occur singly or initiate intracloud flashes. They never come within the interior of flashes. The optical emission does not occur for initiator of strong IC pulse.

e. Strong IC pulse can occur without NBP, but not vice verse.

f. The strong IC pulse in a given storm appear to have a truncated ERP distribution staying below a limiting ERP. For the most storms this is of the order of 1 MW in the FORTE HF band 26 – 48 MHz. The maximal value of a limiting ERP is 10 MW.

3   RB - EAS discharge stimulated by high energy CR particles.

1. RB - EAS discharge is determined by the exponential growth of the number of relativistic electrons, positrons and gamma quants. The characteristic length l_a is given in the Table for the main location heights of PNBP (z=13 km) and NNBP (z=18 km). In RB - EAS discharge the RB process is facilitated significantly in the energy range 3 – 30 MeV due to effective generation of gamma quants and e^+e^- pairs (Dwyer 2003, Gurevich et al 2004a).

Table: RB - EAS and NBP characteristics

$z(km)$	RB-EAS theory			NBP observations	
	l_a(m)	$\tau_g\,(\mu s)$	$\tau_{rel}\,(\mu s)$	$\tau_g\,(\mu s)$	$\tau_{rel}(\mu s)$
13	200	0.7	0.7	1 - 2	2 - 5
18	400	1.4	3	1 - 2	2 - 5

2. The production of a giant number of thermal electrons n_{th} due to ionization of air molecules is going simultaneously with the generation of fast relativistic electrons $n_{th} \sim 10^6 n_f$) (Gurevich et al 2004). So the growth time of thermal and relativistic

electrons coincide. The attachment of thermal electrons to oxygen is due to three particle collisions. The characteristic attachment time (Phelps 1969):

$$\tau_{att} \sim \left(\frac{5 \times 10^{18}}{N_m}\right)^2 \mu s$$

Here N_m – the number density of air molecules in cm $^{-3}$. Attachment determines the relaxation time of discharge. The growth $\tau_g = l_a/c$ and relaxation time of RB - EAS discharge are presented in the Table.

3. The electric current J generated in RB - EAS discharge is unipolar. For a given E_m/E_c its maximum J_m is proportional to the number of thermal electrons. The last is proportional to the number of fast electrons and thus proportional to the number of cosmic ray secondaries. That is why the maximal current J_m is proportional to the energy of cosmic ray particle ε_p. For conditions of strong RB - EAS discharge, using the calculations performed in Gurevich et al 2004a, 2004b, we can estimate J_m as

$$J_m \sim \left(\frac{\varepsilon_p}{10^{17}}\right) \text{kA} \tag{1}$$

Here ε_p is the energy of cosmic ray particle

4. The radio pulse emitted by RB - EAS discharge is bipolar. Its amplitude depends on the distance to the source R and on discharge parameters. In average according to our simple model (1) it is proportional roughly to ε_p.

5. The main energy dissipated in RB - EAS discharge goes to ionization of air molecules and to excitation of N_2 vibration levels. Optic emission is very low – less that 1% of total energy (Roussel-Dupre and Gurevich 1996, Gurevich et al 2004).

4 Discussion

NBP and RB - EAS theory

Let us compare NBP with the theory of RB - EAS discharge generated at high heights 13 – 18 km by very energetic cosmic ray particles ($\varepsilon_p \geq 10^{17} - 10^{19}$ eV). Parameters of RB - EAS discharge at high heights are presented in the Table. One can see that both growth and relaxation time characteristics roughly agree with NBP observations. Electric current is unipolar. Its main peak reaches the values (1) which generally are in agreement with the average data obtained in NBP observations. One can see the following chain of measurements which show the rough proportionality between J_m and ε_p:

Tien Shang experiment (Gurevich et al 2004b)

$$\varepsilon_p \sim 10^{15} \, \text{eV}\,, \qquad J_m \sim 1 - 10 \, \text{A}$$

Lightning first pulse measurements (Gurevich et al 2003)

$$\varepsilon_p \sim 10^{16} - 10^{17} \, \text{eV}\,, \qquad J_m \sim 0.1 - 1 \, \text{kA}$$

NBP

$$\varepsilon_p \sim 10^{17} - 10^{19} \, \text{eV}\,, \qquad J_m \sim 10 - 100 \, \text{kA}$$

Thus RB - EAS discharge can serve as background for explanation of NBP phenomena.

Note that the high values of maximal electric field $E_m/E_c \approx 1.2 - 1.4$ were supposed in estimates Gurevich et al (2004a). The direct observations of electric fields at NBP heights gave lower values yet (Vonnegut et al 1989). On the other hand the NBP are usually seen in the active phase of storm near reflectivity core with 50 dBz radar reflectivity (Smith et al 1999). According to Smith et al 2003 the strong positively charged layer at the heights (15 - 16) km exist between generation maximum of NNBP and PNBP. It is impotant also that NBP formation is accompanied by powerful HF emission.

HF emission model

In Gurevich et al (2004a) RB - EAS model the air density N_m distribution was supposed to be smooth function depending on one coordinate z. In reality in the high reflectivity core where NBP is generated a large number of hydrometeors (liquid or frozen water drops) exist. That can generate significant fluctuations in RB process. Really according to MacGorman and Rust (1998) the characteristic hydrometeor dimensions in a high reflectivity core $r_0 \sim 0.3$ mm and density number $n \sim 10^{-2}$ cm $^{-3}$. Due to this the mean free path of fast electrons between collisions with hydrometeors is $l_{eh} \sim (\pi r_0^2 n)^{-1} \sim 0.3$ km. The effective radiation length of hydrometeors $t_h \approx 0.03 g/cm^2$ is equivalent to the length $l_h = t_h/\rho_{air} \approx 1.5 - 3$ m in the air at the heights 13 - 18 km. It means that the passage of hydrometeor by runaway electron is equivalent to the passage of additional air length l_h. Thus the existence of randomly distributed hydrometeors lead to random fluctuations of N_m and E_m/E_c of the order of $l_h/l_{eh} \sim 1\%$. Taking into account exponential dependence on E_m/E_c of fast and thermal electrons generated in RB process, one can expect that hydrometeors could be the reason of strong enough random fluctuations of electrons and electric current.

Another effect which could be responsible for fluctuations is space inhomogeniety of cosmic ray secondaries which serve as a seeds of RB - EAS process. These fluctuations are especially significant at the high heights of the order $15 - 20$ km where the shower has not reach the full stage of development yet. That is why the showers coming under inclination angle more than 60° are mostly effective The approximation of a quasi flat electromagnetic shower cascade moving together with cosmic ray particle which was used in Gurevich et al (2004a) could be considered as a good approximation for low energy $\varepsilon_p < 10^{15}$ eV only. For the higher energies of cosmic ray particles situation is quite different. Note that laboratory experiments at accelerators in this energy region are absent. Both cosmic ray experiments and theory show very complicated character of shower structure at high energies $\varepsilon_p \geq 10^{17}$eV (Murzin 1988). The observations using Pb and Pb-C cameras in Pamir and Chakaltaya experiments demonstrate multidimensional and inhomogeneous structures of electron - photon shower components (Baiburina et al 1984, Hasegawa and Tamoda 1996). Though photon super families of halo type (Genina et al 1981) and a number of new type processes "Centauro", "Chiron", penetrating chanels, anomalous transition curves (see Gladysz -Dziaoshu 2001, Capdevielle and Slavatinsky 1999) are not well understood, the growth of fluctuations in photon and secondary electrons distribution could exist. In spite of fluctuations the part of the energy of primary cosmic ray particle distributed in electron photon component of the shower is conserved at the level $(0.2 - 0.3)\varepsilon_p$ (Baburina et al 1984). It means that the full power of cosmic ray secondaries is

proportional to ε_p what supports the basic relations (1).

Space and time fluctuations of E_m/E_c and cosmic ray secondaries lead to the corresponding fluctuations in number of generated thermal electrons what results in a strong fluctuations of the current. In that a way we suppose the intensive IC pulse HF radiation is generated.

At the same time these fluctuations do not change the essence of RB - EAS process. Its main features are reflected in IC HF radiation characteristics emphasized by Jacobson (2003). Radio emission is strong but the accompanying optic emission is very low, IC HF emission exists only as a single pulse (or as a first pulse in the beginnings of a flash) and so on.

Coherence effect and the giant power of low frequency radio emission pulse (NBP)

The power dissipated in RB - EAS discharge is approximately proportional to the energy of cosmic ray particle ε_p. The number of created newborn thermal electrons is also proportional to ε_p and to the exponential factor $F(E_m/E_c)$. Factor F in real conditions could reach values $F \sim 10^2 - 10^4$ (Gurevich et al 2003, 2004a). Thus the full energy W_d dissipated by thunderstorm electric field to the creation of thermal electrons and hence to the electric current of RB - EAS discharge is of the order of $\varepsilon_p F$. For $\varepsilon_p = 10^{16}$ eV energy $W_d \sim 1$J, for $\varepsilon_p \sim 10^{19}$ eV $- W_d \sim 1$ kJ. The same is fully correct for a non coherent HF radio emission. Its maximal frequency integrated power is 1–10 MW, maximal emitted energy $(10 - 100)$ J.

The picture changes dramatically when we take into account *coherence of low frequency (LF) emission process*. The pulse current region determined by the EAS scale is $l_a \sim 300 - 400$ m. For LF radio emission $(200 - 500)$ kHz the scale L_c is of the order or less than the length of radio wave $\lambda = (600 - 1500)$m. It means that the LF radio emission is coherent process and due to this the *power of radio emission in LF is growing with current J proportionally to J^2*. That is why the ground wave power in NBP could reach extreme values:

$$P = \frac{2J^2}{3c}, \qquad P \approx (100 - 300)\,\mathrm{GW}$$

It means that emitted by radio pulse energy can reach $0.2 - 1$ MJ. We see that the work of thunderstorm electric field in NBP is really *giant*: it exceeds 10^6 times the energy of cosmic ray particle triggering the process.

We emphasize that the LF coherence effect is a strong argument supporting RB - EAS model of NBP generation. LF coherence means that though HF emission is incoherent but all currents which generate it according to the model *has the same direction*. In other words they have the same nature – thermal electrons moving by thundercloud electric field. These currents are only distributed in space - time inhomogeneously in groups and thin filaments – determined by inhomogeniety of local electric field and cosmic ray secondaries production.

Conventional ohmic electric discharge in the night time ionosphere excited by NBP

According to Smith et al (2003) in the night time conditions the NBP reflection region lies at the hieghts z 80 – 90 km. One can see, that NBP power is so high that electric

field of the pulse E_{nbp} coud reach and overcome the value of conventional breakdown field $E_{th}(z)$ at these heights

$$E_{nbp} > E_{th} = 22 \left(\frac{N_m(z)}{2.7\,10^{19} cm^{-3}} \right) \frac{kV}{cm}$$

where $N_m(z)$ is the number density of air molecules at the height z. For the height 80 km it follows that $E_{th} = 24$ V/m, for the height 90 km $E_{th} = 3.2$ V/m. Thus one can expect that short - time discharge (a few μs) excited by NBP in lower ionosphere could be observed.

Statistics of high energy cosmic rays and NBP events

The flux of cosmic ray particles having the energy $\varepsilon > 5 \times 10^{18}$ eV is one per km^2 per year (Murzin 1988). The annual thunderstorm duration complied from 450 air weather system in USA gives an average number 100 h/year (MacGorman et al 1984, Uman 1987). It means that thunderstorms lasts about 1% of the whole time. The flux of high energy cosmic ray particles ($\varepsilon > 5 \times 10^{18}$eV) in thunderstorm time is $0.01/km^2 year$. The FORTE satellite combined with ground based systems allows to detect simultaneously radio emission at $(1 \div 3)10^6$ km^2. Thus the number of events of interaction of cosmic rays $\varepsilon > 5 \times 10^{18}$eV with thunderclouds is $(1 \div 3)10^4$ per year. In reality if the NBP can be generated by lower energies say 5×10^{17} the statistics would be 100 times better $\sim 10^6$ events per year. Thus we see that there is no contradictions between the NBP observational data (10^5 events during 4 years (Smith et al 2003)) and high energy cosmic ray flux.

Initiator speed

According to observations (Smith et all 1999, Jacobson 2003) the speed of NBP initiator is close to 10^{10} cm/s. The high energy cosmic ray particle (HECRP) moves with velocity of light. But the radio emission of RB -EAS discharge is generated by the current of the thermal electrons which flows in the direction of thunderstorm electric field **E**. Thus the speed of initiator $v = c\,cos\,\theta$, where θ is the angle between **E** and HECRP direction of motion. That explains the difference in initiator speeds. We emphasize that values of observed velocity is not far from c.

We note that for effective development of shower the cosmic ray particle has to pass a thick enough atmospheric layer. At the heights $13 - 18$ km the density of air is low. That is why HECRP has to go under the large inclination angles $\theta \approx 70^o - 80^o$ to obtain well developed shower. Thus the RB - EAS discharge become stronger for HECRP having large inclination angle.

High energy cosmic ray particle detection (preliminary remarks)

The high power of NBP signals allows to detect them at large distances – up to 1000 km. That can be used for detection of cosmic ray particles with energies $\varepsilon_p \sim 10^{18} - 10^{19}$ eV and higher (HECRP). Of course every concrete event depends not only on ε_p but on a number of others factors like E_m/E_c, reflectivity core size, thunderstorm activity. But one can expect that after averaging over a large number of events some useful information about HECRP could be obtained directly from NBP. For example, according to Smith et al (2003) the NBP database has now more 100 000 events. NBP is created by current having maximal value J_m which is proportional to ε_p (1). As the HECRP integral flux

$F(\varepsilon > \varepsilon_p)$ is proportional to ε_p^{-2} one can construct the averaged over all NBP events function

$$Q = \left\langle \Phi(J_m > I_0) \left(\frac{J_m}{I_0}\right)^2 \right\rangle$$

Here Φ is the full number of NBP with $J_m > I_0$ and I_0 is arbitrary chosen current, say 5 kA. A careful selection of PNBP and NNBP homogeneous conditions using HF emission data should be performed. At the middle values $J_m < 100$ kA the function $Q(J_m)$ is expected to be approximately constant what will show that cosmic ray spectrum plays a dominant role. In that case the curve $Q(J_m)$ and its behavior at the highest values $J_m \geq 300$ kA can give evidence of the *existence of GZK cutoff or its absence.*

Here we supposed that up to highest values of J_m flux dependence on ε_p is decisive. The role of other thunderstorm factors should be carefully studied.

5   Conclusion

The analysis presented in the letter allows to formulate the following main statements:

1. Narrow bipolar radio pulses (NBP) are generated by runaway breakdown – extensive atmospheric shower (RB -EAS) discharge initiated in atmosphere by very high energy cosmic ray particles.

2. The detailed analysis of a large NBP data base could be used to obtain unic information about HECRP spectra including a highest energy range. There is a chance to establish the fundamental fact of existence (or non existence) of GZK cutoff.

3. Of special interest is the detailed analysis of giant information gathered in HF radio spectrum observations. These new data analysis being combined with the theory and ground based measurements give a chance to reach some progress in understanding of basic processes in high energy particle physics ($\varepsilon > 10^{16}$ eV).

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